

Original Contributions

THE EFFECTS OF LEAD SULFATE ON NEW SEALED LEAD ACID BATTERIES

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Abstract—Emergency Medical Services (EMS) rely on batteries to power external cardiac defibrillators. While maintenance protocols should be followed to ensure that batteries possess adequate capacity to power their defibrillator, they are not often applied to new batteries. This study examines the effects of prolonged storage on sealed lead acid (SLA) batteries, the number of batteries that are affected by lead sulfate, and the ability of a protocol to restore the capacity in SLA batteries. A prospective cohort of new batteries was subjected to testing and discharge protocols. Initial battery capacities were measured using a battery analyzer. An “over-discharge” protocol fully discharged the battery over a 24-h period, and batteries were recharged and reanalyzed. Capacity measurements were repeated twice. Sulfate buildup was defined a priori as final capacity measurements greater than predischARGE measurements. There were 126 batteries studied, a mean of 14 months after manufacture. Overall, 47 batteries (36.5%) had measured capacity that was insufficient (<65% capacity). Batteries possessing very low initial capacities (<55%) responded with a significant improvement on average of 54.7% compared with batteries within a normal capacity range (>65%) whose average improvement was 9.3%. After discharge, there was an average of 17% improvement in the measured capacity, with no differences in the final capacity readings in each battery type. In conclusion, sealed lead acid batteries are affected by prolonged storage. The loss of capacity created by accumulation of lead sulfate can be reversed if battery maintenance protocols are used as part of EMS quality assurance programs. © 2000 Elsevier Science Inc.

Keywords—EMS; AED; battery capacity; quality assurance

INTRODUCTION

Automatic external defibrillators (AEDs) have been employed in Emergency Medical Services (EMS) since 1979 (1). They provide a means for early defibrillation, which is a vital link in the chain of survival (2–5). Successful prehospital defibrillation is related to a series of events that generally include early cardiopulmonary resuscitation (CPR), prompt EMS access, and short EMS response times. This success is also linked to the correct functioning of the AED and the availability of adequate power to deliver the shock (6, 7).

Characteristics of sealed lead acid (SLA) batteries that make them a suitable choice of power for various types of electromedical equipment include a high tolerance to extended charge cycles, low self-discharge, portability, low maintenance, and low cost. Several AED models use self-contained SLA batteries as their sole power source. SLA batteries also are found in other hospital-based equipment such as portable monitors, infusion pumps, and portable ventilators. However, batteries in these settings often are only a secondary source of power.

The typical 12-volt SLA battery consists of 6 cells comprised of a series of positive plates whose active material is lead dioxide (PbO₂) and negative plates whose active material is lead (Pb). These plates are

immersed in a gelled electrolyte solution of sulfuric acid (H_2SO_4). Upon discharge of the battery (via operating the AED), a chemical reaction occurs that causes the release of energy. Acid from the electrolyte combines with the active material of the internal plates, converting the active material's content to lead sulfate (PbSO_4). During discharge, the electrolyte's pH is lowered as it converts to water molecules ($2\text{H}_2\text{O}$). During recharge, the electrochemical process is reversed; the lead sulfate reverts back to active material while the acidity of the battery increases. Problems exist when the battery is stored in a discharged state or subjected to repetitive deep discharges (<11.0 volts) without allowing it to become fully recharged. The lead sulfate material hardens and renders that portion of the plate useless, reducing the capacity of the battery.

Since the success of AEDs is intimately linked to the reliability and function of these batteries, it is critical for an EMS to implement battery maintenance programs based on individual battery performance. Since battery capacity analysis has proven to be an excellent indicator of battery performance, capacity measurements should be an integral component of battery maintenance programs (8). Such programs can be justified for several reasons. First, battery capacity may deteriorate over time, depending on the characteristics of use. Second, new batteries may have reduced capacity because of a prolonged storage period before use. Recent evidence suggests that reduced capacity in SLA batteries may be related to the accumulation of sulfur deposits ("sulfation") on the internal plates of the battery (9). Batteries stored for a prolonged period of time without receiving a charge, as well as batteries stored in a discharged state for a period of time, are most susceptible to lead sulfation. This battery deterioration can remain undetected in the absence of battery maintenance protocols. If undetected, the battery's capacity may be inadequate to power the AED, jeopardizing treatment of critically ill patients.

It has been suggested that when reduced battery capacity is related to sulfur accumulation, an "over-discharge" protocol can restore the battery's capacity (9). Typically, SLA batteries are not discharged below 1.75 volts per cell or a voltage at the terminals of 10.5 volts, as in the 12-volt SLA batteries used by AEDs. An over-discharge protocol discharges the battery to a terminal voltage of zero volts. By converting the active material entirely to lead sulfate through this over-discharge protocol, the active material can be restored to its original state of lead dioxide during the recharge portion of the protocol.

The objectives of this study were to:

1. Determine what percentage of newly purchased SLA batteries demonstrate reduced capacity.

Table 1. Analysis Protocol as Programmed into the C4000 Battery Analyzer

Number of cells	6
Battery rating	2 Ahr
Charge/discharge rate	600/1,000 milliamps
Max. charge voltage	2.45 volts/cell
Termination current	100 milliamps
End of discharge	1.75 volts/cell

2. Determine the ability of an over-discharge protocol to restore capacity.

MATERIALS AND METHODS

Basic Electrical Theory

All batteries have a "capacity rating" expressed in ampere-hours. This rating, established by the battery manufacturer, indicates the battery's ability to deliver a specified current over a period of time under specified conditions (9). In this study, the actual battery capacity was determined using a fully automated battery analyzer (Cadex C4000: Cadex Electronics Corp., Burnaby, British Columbia, Canada). This equipment measures the percent capacity on any commonly used battery (e.g., sealed lead acid or nickel cadmium) based on criteria programmed into the analyzer by the user (Table 1). The Cadex battery analyzer has an accuracy range of $\pm 2.5\%$.

Design

A prospective evaluation of 126 newly purchased batteries was performed to determine capacity. To remove any bias in handling practices or manufacture, all batteries shared the same manufacturer, possessed the same manufacturing date (lot code), and were received in one shipment. All testing was completed within a 3-week period.

Setting

The Ottawa Hospital Paramedic Program has 95 automatic external defibrillators in use. The models include Heartstart 3000 QR and 3000 ATS, all manufactured by Laerdal Medical Corp. (Stavanger, Norway). These units are distributed to area fire departments and ambulance services throughout the Regional Municipality of Ottawa-Carleton, which covers 2,757 sq. km. The Institutional Biomedical Engineering Department maintains all AEDs and batteries.

Testing Protocol

Testing was performed by one technologist. All batteries were tested before system use, and elapsed time from production was recorded. Each battery was subjected to capacity analysis (Table 1) using the automated battery analyzer. The batteries were then discharged for 24 h via 10-ohm power resistors, and the final discharge voltage of the battery was recorded. After a stabilizing period of 1 h, the depleted batteries were recharged for 24 h and capacity analysis was repeated.

Outcomes

Each battery was subjected to the same testing protocol. Five capacity measurements were recorded for each battery, three before the over-discharge cycle and two post-discharge cycle. The average of the postdischarge cycle measurements was compared with the highest capacity before the discharge cycle and was expressed as a percent improvement (post-pre/pre). A successful response was recorded when batteries possessed a final postdischarge capacity of 65% or greater.

Statistical Considerations

All data were entered and analyzed with StatView SE statistical software (Abacus Concepts, Inc. Berkeley, CA.). Categorical variables are reported as counts and percentages (%). Continuous variables are reported as means with either standard deviations (SD) or 95% confidence intervals (95% CIs). The difference between means was analyzed using paired Student *t* tests and analysis of variance. A $p < 0.05$ was used to indicate statistical significance.

Ethics

Ethics review for this study was waived by the Ethics Review Board of the institution since no patient identifiers were recorded.

RESULTS

A total of 126 newly purchased SLA batteries were analyzed. The average length of time from production to assessment was 14 months.

From the sample, 46 (36.5% of sample; 95% CI: 28–46) of the newly purchased batteries had capacities below our acceptance threshold of 65% capacity (Table

Table 2. Incoming Inspection Results Before Over-Discharge Protocol With Respect to Acceptance Thresholds

Measured Capacity	<65% Capacity (Fail) <i>n</i> = 46	>65% Capacity (Pass) <i>n</i> = 80
Minimum	39%	65%
Maximum	64%	77%
Average	57.8%	69.4%

2). Thirteen batteries (10.3% of sample; 95% CI: 6–17) exhibited very low capacities, and a further 37 batteries (29.4% of sample; 95% CI: 22–34) exhibited low capacity readings. Under normal circumstances, batteries failing to meet these standards would be returned to the manufacturer.

Following discharge protocol, all 126 (100%) significantly improved their measured capacity. Capacity gains following the protocol were based on initial battery capacity. For example, batteries with the lowest initial battery readings improved by 54.7% (95% CI: 44–65), whereas low (23.5% improvement; 95% CI: 21–26) and normal (9.3% improvement; 95% CI: 8–10) capacity batteries increased by lesser amounts. There were no statistically significant or clinically important differences in capacities between the three battery levels at the conclusion of the protocol ($p = 0.34$). Overall, there was a 17% improvement in the measured capacity of the batteries after an over-discharge protocol was implemented.

DISCUSSION

Reliable AED equipment components are important factors in successful out-of-hospital EMS cardiac arrest programs. This study has demonstrated the value of a quality assurance program for batteries, one component of the AED equipment. The results identify a high frequency of insufficient battery capacity in new SLA batteries, particularly when batteries are in storage for a prolonged period. This problem appears to be related to lead sulfate buildup, and would remain undetected without sufficient safeguards. Moreover, these batteries normally would be distributed by most systems before inspection, which may result in premature failure of the battery.

The over-discharge protocol described here and applied in this study consistently restored battery capacity. In all cases, these capacities returned to acceptable levels, saving the expense, time, and environmental damage associated with battery disposal. Before honoring warranty replacement of a battery, most manufacturers will

Table 3. Comparison of Initial and Final Battery Capacities Based on Initial Capacity Levels

Levels	N	Initial			Final		
		Range	Mean	SD	Range	Mean	SD
Very low	13	<55	50.1%	4.42	71–80.5	76.8%	2.26+*
Low	37	56–65	61.3%	2.63	67–80	75.5%	2.88+*
Normal	76	>65	69.6%	2.49	70.5–82	75.9%	2.69+*

Notes: Initial = reading before over-discharge protocol; Final = capacity after over-discharge and recharge; + = significant differences between initial and final capacity recording based on level (*t*-test; $p < 0.001$); * significant differences between groups for change in capacity (one way ANOVA; $p < 0.001$).

test the questionable battery. However, the manufacturer's testing criteria are often based on the battery's rated capacity and not its end use. Therefore, the discharge currents used during such testing may be much lighter than the one outlined in Table 1. Our test protocol replicates loads placed on the battery during normal usage within the AED, as well as having an established correlation between battery capacity and the number of 360-joule shocks an AED can deliver (8). We suggest that ensuring that newly purchased batteries are at their highest capacity requires the incorporation of such an over-discharge protocol into incoming inspection protocols.

Based on analyzed data collected over many years, our acceptance threshold for new batteries in this program is a capacity of 65% of rated capacity or greater. If not for the over-discharge protocol, 36.5% of the batteries would have failed to meet the acceptance criteria (Table 2). A system that does not offer capacity measurements on newly purchased or existing batteries has no quantitative indicator of the battery's ability to perform and may be subject to a greater number of battery-related failures during patient treatment.

Self-discharge is an infrequently recognized but potential contributor to capacity loss (9). However, SLA batteries possess a low self-discharge rate, and previous documentation of this phenomenon is rare. Manufacturers state that the typical self-discharge of an SLA battery is a 10% loss of capacity every 3 months. All the tested batteries were manufactured on the same date, as documented by the manufacturer's lot code. The average delay to usage was 14 months. Since manufacturers' specifications on self-discharge imply a fixed rate of capacity loss for a given model of battery, the specification may be misleading considering the wide range of our initial capacity measurements (Table 3). This "buyer beware" message is especially important to those Emergency Medical Services that change battery distributors frequently in search of a better price.

There is a paucity of information regarding battery

testing and acceptance or rejection criteria. Manufacturers' estimates of expectant life may be conservative, but they are based largely on the age of the battery or the number of shocks it has delivered. Such an assumption fails to recognize the issues described above. Moreover, an EMS system that fails to test individual batteries, even new ones, against premature loss of capacity may be placing patients, paramedics, and its AED program at some risk of litigation if the AED fails to function. An evidenced-based approach to testing individual batteries against protocols outlined in this study offers quantitative measures and increases confidence in the AED's ability to perform in the field.

Manufacturers and distributors of batteries could help minimize the effects of self-discharge by certifying that their batteries, upon receipt by the customer, will possess an acceptable amount of capacity. Furthermore, users could request that newly purchased batteries have a minimal delay between production and delivery.

Potential flaws in EMS battery protocols that may contribute to the premature loss of capacity of an SLA battery include depth of discharge, duration of recharge cycles, and incoming inspection protocols. Sealed lead acid batteries may last several months to several years depending on how they are used (9). In a high call volume service, a battery may remain in the AED until it is no longer able to power the unit; thus, the battery would be considered fully discharged. Used continually in this fashion (fully charged to fully discharged), the battery will last for an estimated 200 charge-discharge cycles, which may equate to 6–10 months. On the other hand, in services with a low call volume, the battery may be used infrequently. It may last for up to 1,500 charge-discharge cycles or 4–5 years; typical recharge times for SLA batteries range from 16–24 h (9). These recharge times should be respected regardless of the type of service in which the batteries are used or the service's call volume.

While these observations are alarming, there are several limitations to this study. First, the study examined only one type of SLA battery. While others are on the market, it is possible, though unlikely, for each SLA battery to behave differently. In addition, storage, handling, and environmental exposures were not documented. While this may potentially exacerbate the sulfation problem, we suggest that the cooler Canadian environment is less damaging than more southern latitudes with warmer weather. Therefore, the results here may underestimate the problem. The follow-up on batteries that were over-discharged is incomplete. However, early results suggest that the batteries in service are functioning well.

Finally, this study does not address the economic impact of the over-discharge protocol. Comparing the

savings by “resuscitating” batteries with the cost of implementing such a program is beyond the scope of this research project.

While the over-discharge protocol is beyond traditional testing of SLA batteries, the system described ensures that new batteries are tested for premature capacity loss by individual capacity measurements. Batter-

ies possessing capacities $< 65\%$ may require an over-discharge protocol to ensure that the active material of the battery’s internal plates is restored. Manufacturers’ guidelines do not address concerns such as premature capacity loss or acceptance criteria of new batteries. Implementing this protocol will enhance the quality assurance program of an EMS.

REFERENCES

1. Diack AW, Welborn WS, Rullman SB, et al. Automatic cardiac resuscitator for emergency treatment of cardiac arrest. *Med Instr* 1979;13:78–83.
2. Cummins RO, Ornato JP, Thies WH, et al. Improving survival from sudden cardiac arrest: the “chain of survival” concept. A statement for health professionals from the Advanced Cardiac Life Support Subcommittee and the Emergency Care Committee, American Heart Association. *Circulation* 1991;83:1832–47.
3. Eisenberg MS, Horwood BT, Cummins RO, et al. Cardiac arrest and resuscitation: a tale of 29 cities. *Ann Emerg Med* 1990;19:179–86.
4. Roth R, Seward RD, Rogers K, et al. Out-of-hospital cardiac arrest: factors associated with survival. *Ann Emerg Med* 13:237–43.
5. Brison RJ, Davidson JR, Dreyer JF, et al. Cardiac arrest in Ontario: circumstances, community response, role of prehospital defibrillation and predictors of survival. *Can Med Assoc J* 1992;147:191–9.
6. White RD. Maintenance of defibrillators in a state of readiness. *Ann Emerg Med* 1993;22:302–6.
7. Cummins RO, Chesemore K, White RD, et al. Defibrillator failures. *JAMA* 1990;264:1019–25.
8. Cleland MJ, Maloney JP, Hay JL, et al. Relationship between battery capacity and the delivery of shocks in prehospital defibrillators. *Prehosp Disaster Med* 1997;12:132–5.
9. Matsushita Electric of Canada, Ltd., Panasonic Industrial Division: Sealed Lead-Acid Batteries Technical Handbook; 1998.